Cryogenics 51 (2011) 609–612

Contents lists available at SciVerse ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Technical Note

A three-stage Stirling pulse tube cryocooler operating below the critical point of helium-4

L.M. Qiu, Q. Cao, X.Q. Zhi, Z.H. Gan *, Y.B. Yu, Y. Liu

Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, PR China

ARTICLE INFO

Article history:
Received 17 June 2011
Received in revised form 19 July 2011
Accepted 21 July 2011
Available online 3 August 2011

Keywords:
Pulse tube cryocooler
Three-stage
Critical point
Helium-4
Cold inertance tube

ABSTRACT

Precooled phase shifters can significantly enhance the phase shift effect and further improve the performance of pulse tube cryocoolers. A separate three-stage Stirling pulse tube cryocooler (SPTC) with a cold inertance tube was designed and fabricated. Helium-4 instead of the rare helium-3 was used as the working fluid. The cryocooler reached a bottom temperature of 4.97 K with a net cooling power of 25 mW at 6.0 K. The operating frequency was 29.9 Hz and the charging pressure was 0.91 MPa. It is the first time a refrigeration temperature below the critical point of helium-4 was obtained in a three-stage Stirling pulse tube cryocooler.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

The space applications of compact cryocoolers have been extended to sub-10 K in order to meet the cooling requirements for mid-infrared instruments, low-Tc electronics and other applications [1]. The Stirling pulse tube cryocooler is a promising candidate for its advantages of high reliability, low vibration, and easy stage coupling due to the lack of moving parts [2] at low temperatures. Multistage structures have to be applied in order to achieve the low temperatures required to intercept the regenerator losses of upper stages. Although helium-3 can significantly decrease regenerator losses [3,4] because of its superior properties at low temperatures, it is rare and expensive. Until recently, Stirling pulse tube cryocoolers with three stages [5] or even four stages [4] using helium-4 have never achieved liquid-helium temperatures, mainly because of the difficulty of phase shifting with a small acoustic power. It is important to further improve the cooling performance and simplify the structure of the cryocooler in particular for space applications. We have found that it is possible to reach temperatures below 4.2 K with sufficient precooling and efficient phase shifting [6]. This paper presents the experiment results, which verify the phase shifting effectiveness of a cold inertance tube.

2. Three-stage structure

A separate three-stage SPTC [7] (Fig. 1) has been designed and constructed. The three stages are thermally coupled with three thermal bridges (TB (1–2), TB (1–3), TB (2–3)); a design that provides the advantages of less interference amongst the stages, and independent operating parameters (e.g. frequency and charging pressure) for better performance. The regenerator generates a small amount of enthalpy flow due to imperfect regeneration, which adds to the heat load of the cold end and degrades the performance. The enthalpy flow can be intercepted by precooling, that may improve the performance. The heat load is intercepted by the thermal bridge TB (1–2) for the second stage and intercepted by the thermal bridges TB (1–3) and TB (2–3) for the third stage at different temperature ranges.

3. Phase shift analysis

The phase shifter, generally located at the hot end of the pulse tube, shifts the phases of the mass flow and pressure waves, allowing the mass flow to lag the pressure wave. An optimized phase relationship means that the mass flow and pressure waves in the midpoint of the regenerator are nearly in phase, and that the phase span of the mass flow in the regenerator is not too large [8]. Such a relationship decreases the mass flow amplitude for a fixed PV power, thereby decreasing the regenerator loss [9].

Inertance tubes serve as an efficient phase shifter for the SPTC, in which the oscillating gas shifts the phase relationship between the mass flow and pressure waves due to the inertia effect [10].

* Corresponding author. Tel./fax: +86 571 87951930.
E-mail address: Gan_zhihua@zju.edu.cn (Z.H. Gan).

0011-2275/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cryogenics.2011.07.007

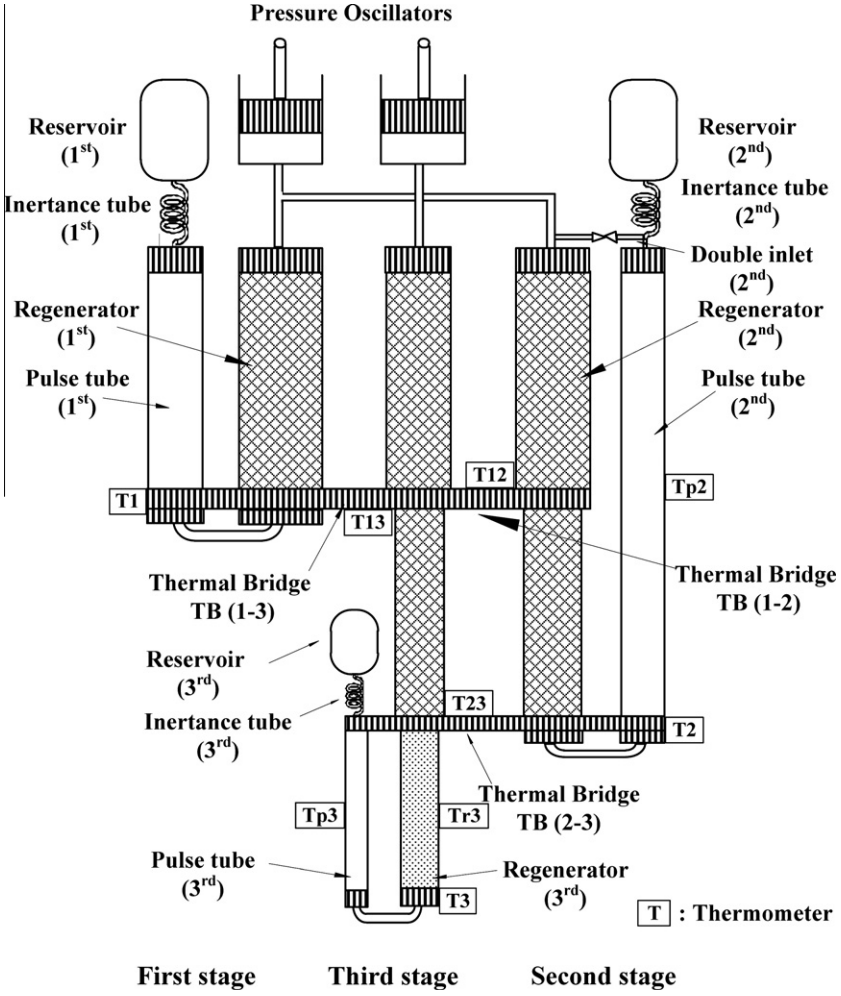

Fig. 1. Sketch of the three-stage Stirling pulse tube cryocooler.

The phase shifting capability depends on the PV power into the inertance tube. With the optimization calculation based on the transmission line model [11], a PV power of 10 W may generate a phase shift of over 25° at 30 Hz with 1 MPa, while only a 5° phase shift can be generated for 1 W (Fig. 2).

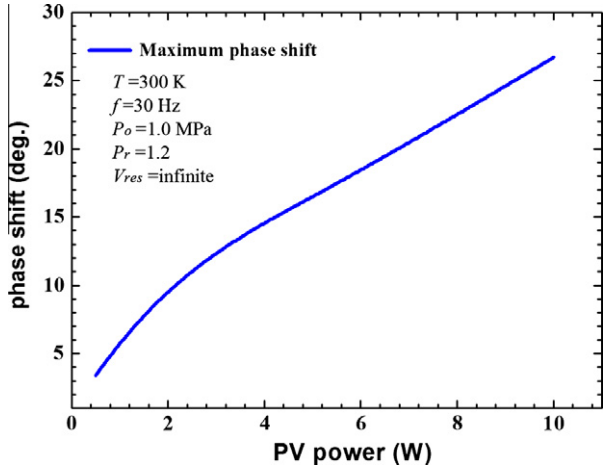

Fig. 2. Maximum phase shift as a function of the PV power into the inertance tube.

The PV power into the inertance tube for a sub-10 K SPTC is usually small. The PV power in the regenerator proportionally decreases with the temperature as the specific volume decreases, and further decreases approximately in half again because of frictional losses. The pressure amplitude also decreases about 50% due to frictional losses. For example, the PV power of 60 W from the pressure oscillator (300 K) decreases to about 0.5 W at the cold end (5 K), and a pressure ratio of 1.4 at the pressure oscillator decreases to about 1.2 at the cold end. In contrast, the PV power and the pressure ratio remain essentially constant from the cold end to the inlet of the inertance tube. At this low power, the maximum possible phase shift (Fig. 2) is far from the desired value for an inertance tube working at ambient temperature. Fortunately, the phase shifting capability can be improved by decreasing the temperature of the inertance tube[12,13]. The maximum phase shift is over 60° at 20 K even for a PV power of 0.5 W (Fig. 3). The improvement is attributed to the increase of density and the decrease of viscosity at low temperatures [6,14].

The third stage is designed to operate with an input PV power of 60 W, which decreases to about 0.5 W at the cold end when operated at 5 K. The desired phase shift can be achieved only with cold phase shifting. An optimized series-connected inertance tube of 2.0 mm × 0.91 m (inner diameter by length) and 3.0 mm × 1.21 m, with the larger one connected to a reservoir of 50 cm^3, provides a phase shift of about 65° at 20 K, which is favorable for the cooler. The pressure ratio is about 1.18 at the inlet of the inertance tube.

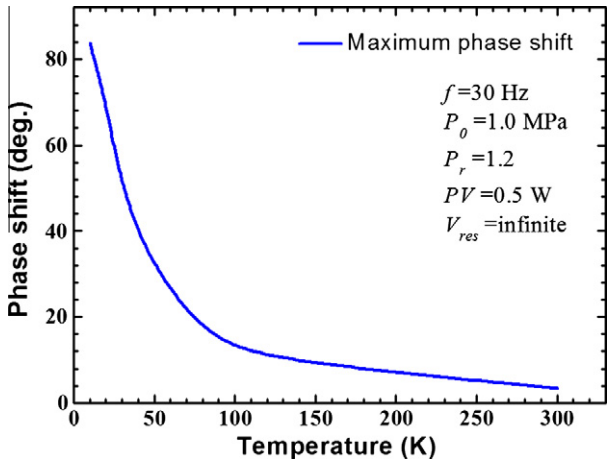

Fig. 3. Maximum phase shift for optimized inertance tube as a function of working temperature.

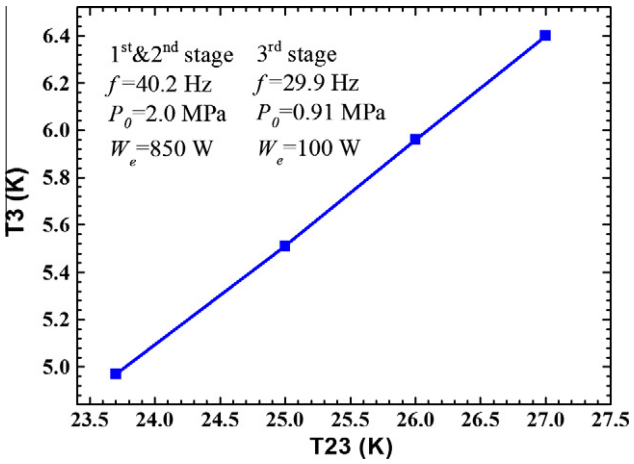

Fig. 5. Effect of precooling on the bottom temperature for the three-stage SPTC.

4. Experiment results and discussion

The first and second stages were driven with one pressure oscillator working at 40 Hz and a charge pressure of 2 MPa, while the third stage was driven with another pressure oscillator working at about 30 Hz and a charge pressure of 1 MPa, which allows an independent optimization of the third stage. Four calibrated piezoresistive pressure sensors were used to measure the pressure at the aftercoolers and warm heat exchangers. Nine calibrated thermometers were used to measure the temperatures. Cernox thermometers, Rhodium–iron resistance thermometers and Platinum resistance thermometers were used for temperatures below 10 K, 10–80 K and above 80 K, with sensitivities of 0.01 K, 0.1 K, and 0.1 K, respectively. Thermometers arranged along the thermal bridges were used to measure the precooling heat flows. Resistance heaters were used for measuring the cooling capacity of each stage.

The preliminary test shows that a lowest temperature of 4.97 K has been achieved (Fig. 4). A cooling power of 25 mW at 6.0 K was obtained with an input electrical power of 100 W to the third stage. Note that the PV power at the after cooler was estimated to be about 60 W because of the low efficiency of the pressure oscillator (about 70%) and the long connecting tube (0.5 m). The working frequency was 29.9 Hz and the charging pressure was 0.91 MPa. The first stage provided a precooling temperature of about 95 K (T12 and T13); the second stage provided a precooling temperature of 23.7 K (T23) with a precooling power of 1.97 W. The input electrical power to the first and second stages was 850 W.

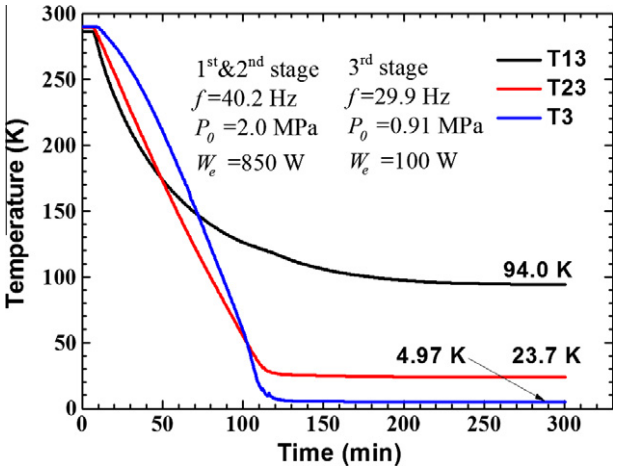

Fig. 4. Cool-down process of the three-stage SPTC.

Increasing the precooling temperature (T23) decreases the phase shifting capability of the third stage, which degrades the performance of the third stage. The no-load temperature (T3) increased by 1.43 K as the precooling temperature (T23) went up from 23.7 K to 27.0 K (Fig. 5). The precooling temperature (T23) also influences the performance of the regenerator and pulse tube of the third stage directly. As T23 increases, the temperature gradient grows larger, and the performance of the regenerator and pulse tube decreases. The effect is not significant, and can be likened to a two stage SPTC with ambient phase shifting [15].

For a wider range of investigation, the optimization of the first and second stages will be carried out in the near future. Meanwhile, a further investigation of the precooling effect, including a measurement of mass flow and pressure in the phase shifter, will be performed.

5. Conclusions

We have demonstrated that a three-stage SPTC with a cold phase shifter can achieve a temperature below the critical point of helium-4. The temperatures of the three stages are 94.0 K, 23.7 K and 4.97 K, respectively. The inertance tube and reservoir of the third stage was precooled by the second stage. Efficient phase shifting has been achieved even with a small PV power of about 0.5 W. The precooling temperature significantly influences the phase shift because both the density and viscosity vary with the temperature, and the influence is reflected by the no-load temperature of the third stage. Further investigation into the precooling phenomena will be carried out.

Acknowledgements

The project is supported by National Funds for Distinguished Young Scientists of China under Contract No. 50825601 and partly by the Major State Basic Research Development Program of China under Contract No. 2011CB706501. The authors acknowledge David Gedeon for constructive discussion.

References

[1] Ross RG, Boyle RF, Key RW, Coulter DR. NASA advanced cryocooler technology development program. In: Mather JC, editor. Proceedings of the society of photo-optical instrumentation engineers (SPIE) 4850. Bellingham: Spie-Int Soc Optical Engineering; 2003. p. 1020–8.

[2] Backhaus S, Swift GW. A thermoacoustic Stirling heat engine. Nature 1999;399(6734):335–8.
[3] Xu MY, De Waele A, Ju YL. A pulse tube refrigerator below 2 K. Cryogenics 1999;39(10):865–9.
[4] Nast T, Olson J, Roth E, Evtimov B, Frank D, Champagne P. Development of remote cooling systems for low-temperature, space-borne systems. Cryocoolers 2007;14:33–40.
[5] Olson J, Nast TC, Evtimov B, Roth E. Development of a 10 K pulse tube cryocooler for space applications. Cryocoolers, vol. 12. New York: Kluwer Academic/Plenum Publishers; 2003. p. 241–6.
[6] Gan ZH, Li ZP, Chen J, Dai L, Qiu LM. Design and preliminary experimental investigation of a 4 K Stirling-type pulse tube cryocooler with precooling. J Zhejiang Univ: Sci A 2009;10(9):1277–84.
[7] Cao Q, Qiu LM, Gan ZH, Yu YB, Zhi XQ. A Three-stage Stirling pulse tube cryocooler approaching 4 K. Cryocoolers, vol. 16. New York: Kluwer Academic/Plenum Publishers; 2011. p. 19–26.
[8] Vanapalli S, Lewis M, Gan ZH, Radebaugh R. 120 Hz pulse tube cryocooler for fast cooldown to 50 K. Appl Phys Lett 2007;90 (7).
[9] Cao Q, Gan ZH, Liu GJ, Li ZP, Wu YZ, Qiu LM, et al. Theoretical and experiment study on a pulse tube cryocooler driven with a linear compressor. Cryocoolers 2009;15:149–56.
[10] Kanao K, Watanabe N, Kanazawa Y. A miniature pulse tube refrigerator for temperatures below 100 K. Cryogenics 1994;34(1):167–70.
[11] Radebaugh R, Lewis M, Luo EC, Pfotenhauer JM, Nellis GF, Schunk LA. Inertance tube optimization for pulse tube refrigerators. Adv Cryogenic Eng, vol. 51. Keystone: CO; 2006. p. 59–67.
[12] Wilson KB, Gedeon DR. Development of single and two-stage pulse tube cryocoolers with commercial linear compressors. Cryocooler 2003;12:139–47.
[13] Olson JR, Mateo S. Cold inertance tube for multi-stage pulse tube cryocooler; 2005 Mar 15, Patent no.: US 6983610 B1.
[14] Gan ZH, Fan BY, Wu YZ, Qiu LM, Zhang XJ, Chen GB. A two-stage Stirling-type pulse tube cryocooler with a cold inertance tube. Cryogenics 2010;50(6–7):426–31.
[15] Yang LW. Investigation on a thermal-coupled two-stage Stirling-type pulse tube cryocooler. Cryogenics 2008;48(11–12):492–6.